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DEVELOPMENTS IN XLPE-INSULATED UNDERGROUND DISTRIBUTION CABLE

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This report examines the current status of XLPE-insulated power cables, and the new designs that are being offered. As well as using the information available on in-service cable performance to estimate the life of older cable designs, a **CONSERVATIVE ESTIMATE** is derived for the expected life of current cable designs and new optional designs based on the present understanding of failure modes in medium voltage power cables. An examination of current cable standards is presented and recommendations for changes are made, especially to incorporate the effect of these new cable designs on cable specifications.

1.0 INTRODUCTION

Although utilities generally have had good experience with underground power cables, many utilities in North America have experienced high failure rates on some parts of their system. This has raised concern about the long-term reliability of the solid-dielectric primary-distribution power cables (5-35 kV class) currently being used by many utilities. In response to this concern, cable manufacturers and other researchers have been investigating improvements in power cable designs, materials, manufacturing, and testing. Over the 15-20 years that this research has been carried out, a large amount of information and many opinions have been generated on the subject. There is now a wide choice of new products, some at a substantial cost premium, purporting to give more reliable service. The MEA has commissioned this report to help utility engineers understand recent developments, so that they can develop cable standards that will result in the installation of the most appropriate cable.

The objective of this work is to provide guidance to utility engineers on the performance of current distribution-class cable and the effect of product improvements on performance. This involves listing recent developments, examining their effect, recommending test methods for their evaluation, and providing the technical information necessary to do cost benefit analyses.

job	file	date	report no.
14-743-643	811.42	February 21, 1989	89-26-K

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Because of the competitive nature of the cable market and changes due to sales volume, the price of the optional cable designs could vary markedly in short periods of time. This means that the results of any cost benefit analysis can only be used as a guide since the price actually paid for optional cable designs could differ from that used in the analysis.

To gain any of the benefits available from current cables or the new designs, it is essential that the cables be handled and installed carefully. Although outside the scope of this report, this point should be remembered if optimum life is to be gained from the product.

2.0 EVALUATION OF CABLE LIFE

The expected life of cable is **ESTIMATED** several times in this report. Because the information necessary to calculate the life function for cable is not available at this time, the following approach is taken. From the survey statistics, a value for the life of 15- to 20-year-old cable designs can be determined. This forms one basis for the estimates of cable life. All changes from that old design, including those used in current cables and those available as options, have been evaluated with respect to the known failure mechanisms in distribution-class cables and are ranked according to their expected effectiveness at prolonging cable life. The changes are described in detail in Appendices A and B. The assumed main failure mechanism, water treeing, is described in Appendix D. It is assumed that each change could be evaluated separately for its effect on extending cable life and that the effect of two or more changes would be approximately the sum of the individual extensions.

The second basis for the estimates consists of choosing the cable option expected to be the most effective, and setting the number of years it adds to cable life. The values of life extension for the other changes are chosen relative to this number. The choice of the most effective cable change and the rankings are discussed in Appendix D.

In arriving at estimates for the life of cables, the main emphasis is to produce **CONSERVATIVE** assessments. For cables expected to last more than 30 years, mechanisms other than water treeing may play a significant role, and the additive assumption of the effect of cable changes becomes suspect; therefore estimates over 30 years have been reduced by 15%.

3.0 CURRENT STANDARD CABLE DESIGN

To help clarify the discussions that follow, Figure 1 shows the cross-section of the current cable design. The high-voltage, inner conductor is covered by an extruded layer of semiconductive crosslinked polyethylene which acts as a shield to reduce any stress enhancements from the conductor wires. The insulation is extruded over this conductor shield. A second shield of semiconductive polymer is extruded on top of the insulation. This layer evens out electrical stress near the concentric neutral conductor. The neutral is helically wrapped over the insulation shield, and may consist of wires or a flat metal tape. The whole cable is often covered with a plastic jacket.

To properly evaluate the benefit of new cable designs, the expected performance of currently installed cables must be known. No direct information is available on even the ten-year performance of current cable designs, since many changes have been made in materials and processing during that time. By examining the performance of the older designs and the changes that have been made, an opinion on the expected life of current cable designs can be formed. Although the estimates given in this report are the author's, the information on current cable technology depends heavily on discussions held with four Canadian manufacturers (Alcan, Canada Wire, Phillips, and Pirelli) and a CEA position paper on polymeric-insulated cables [1].

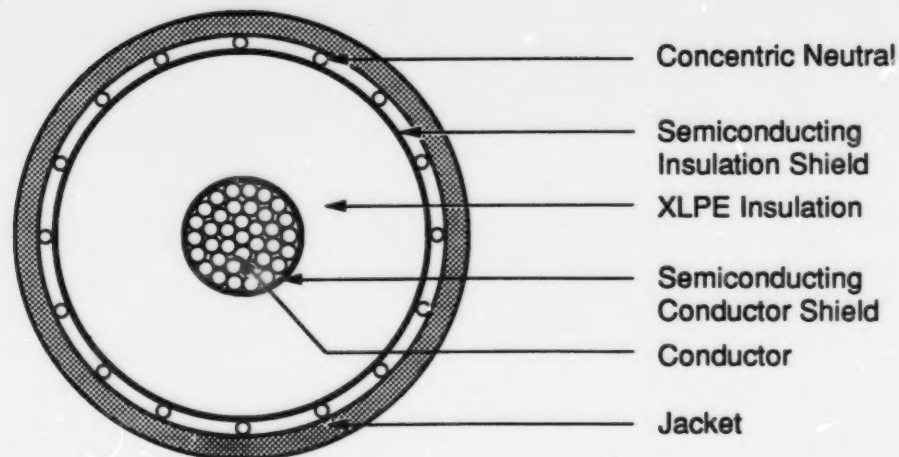


Figure 1 Diagram of a standard concentric neutral power cable.

Table I

SIGNIFICANT CHANGES IN DESIGN AND MANUFACTURING PRACTICES

	Description of Changes	Significance to Cable Life
insulation	- now mostly extra-clean XLPE	- reduces early faults from electrical trees and large water trees from contaminants
conductor	- copper or aluminum - use wider variety of types of stranding	- except solid, stranding type unimportant - effect of Cu and Al ions in water trees is unknown; possible gas evolution with Al
shields conductor insulation	- semiconducting - bonded extruded thermosetting material - extruded thermosetting PE copolymer - stripable	- well bonded extruded shield far superior to uncoated tapes at reducing streamer water trees
processing	- better control systems, dual tandem - "dry" cure and true triple extrusion	- better controls should give a more consistent product; ie fewer voids, good dimensions - single pass extrusion has the potential for producing good shield-insulation interfaces; less conductor shield damage
material handling	- attempting to keep dust and dirt out of insulation; less attention has been paid to semi-con cleanliness	- similar to the effects of cleaner insulating compounds
jackets	- requested by more utilities	- reduces mechanical damage to the cable - reduces possibility of neutral corrosion - if not damaged may impede the ingress of moisture

Table I lists the important changes that have occurred in the past 10 to 15 years. A more detailed description of the changes and their significance is given in Appendix A. The efforts to produce a cable with clean, void-free insulation, and with semiconductive shields that do not promote insulation degradation are particularly important. Many of these changes have come out of the realization that moisture can significantly degrade polymeric insulation, and that, in spite of high initial dielectric strength, these materials must be produced carefully and handled properly to obtain maximum cable life.

3.1 Expected Performance - Comparison of Old Design and Current Cables

The performance of old design cables has been monitored over the last 20 years [eg references 2-6]. The CEA has been collecting information from Canadian utilities since 1983 [2,3]. From the information on North American failure rates, some approximate figures for the expected life of these cables (ie when failure rates go above 3 faults per year per 100 km) were derived and are given in Table II.

Table II
APPROXIMATE "LIFE" FOR OLD DESIGN CABLES

Design ¹	Approximate Expected Life ² Based On	
	Average System Age ³	Cable Age ⁴
Butyl rubber insulation	3 - 6 years	3 years
High molecular weight PE - not clean compounds - various shields	7 - 9 years	6 years
Cross-linked PE - not clean compounds - tape shields - 5 kV - 15 kV	7 - 8 years 10 - 15 years	6 years 13 years

¹ All these cables were made on equipment without modern control systems or any of the new precautions concerning cleanliness. Most cables were unjacketed.

² Expected life is the approximate cable age (either average cable system age or actual cable age) when failure rates exceed 3 faults per 100 km per year.

³ Average cable age is the length weighted average of the age of cable on a system. Data on these failure rates was extrapolated from CEA and AEIC surveys.

⁴ These numbers, which are based on the age of individual cables, are estimates.

A conservative estimate of the effectiveness of the new features in prolonging cable life is given in Table III. It is difficult to predict the performance of new cables. The results of short term tests cannot be applied to predicting field life at this time, although work towards this result is currently in progress under EPRI contract RP2713. Because solid insulations have no self-repairing mechanism, imperfections invariably lead to cable breakdown. Since a low percentage of cable defects per unit length can lead to an unacceptable failure rate, it is

difficult to quantify the beneficial effect that procedures to produce clean, void-free insulation will have. Therefore, the numbers in Table III are only ESTIMATES based on a ranking of the expected effects of the changes, based on the author's experience. The handling and installation practices of the utilities can have a great effect on the cable's performance, and thereby affect the performance improvement.

Table III

ESTIMATES OF THE EFFECT THAT MANUFACTURING CHANGES
HAVE HAD ON THE EXPECTED LIFE OF CURRENT DESIGN CABLES

Change	Effect on Cable Life	
- extra-clean XLPE - improved material handling	- lower initial failures and slower water degradation	- could add <u>approx. 2 years</u>* to average cable life
- improved extruded thermoset shields	- slower water treeing	- could add <u>approx. 3 years</u>* to average cable life
- processing changes	- should have fewer cables with poor records - fewer vented water trees	- could add <u>approx. 2 years</u>* to average cable life if no chemical changes
- jackets	- mechanical protection would reduce early failures - reduction in cable wetting and neutral corrosion	- could add <u>approx. 2 years</u>* to average cable life

* These values for added life are CONSERVATIVE estimates based on the ranking of all cable changes and options as described in Appendix D.

From summing the values in Tables II and III, a conservative estimate for the average life of current cross-linked polyethylene cables is ~22 years, assuming care was taken in manufacture and handling.

4.0 OPTIONS TO THE CURRENT CABLE

There have been advertising claims that several optional materials and processing changes can lead to improved product performance. Table IV lists the alternatives to the currently available standard cable and gives a quantitative assessment of their improvement to cable life. A full description of alternate cable designs, materials and manufacturing processes, as well as some of the rationale for the assessment, are given in Appendix B. Much of the work in this section was based on a CEA position paper [1].

Not all the cable improvements listed in Table IV can be added together to estimate cable life, since some are mutually exclusive. For example, the benefits of full metal sheaths and PE coated foils would not be additive since they would not be used together. Some reasonable combinations of options are evaluated in Table V based on the numbers given in Table IV. No attempt has been made to evaluate the cost effectiveness or the difficulty in implementing the options shown; they are presented as guides to the kind of cables which may be used by the

utilities. It should be remembered that the values given in all of the tables depend heavily on the quality of INSTALLATION (handling, methods and workmanship) BY THE UTILITY.

Table IV
OPTIONAL CABLE DESIGNS AND PROCESSES

	Alternative	Status	Effect on Cable Life	Added Life
insulation	- non-fugitive tree retardant compounds - thicker insulation	available	- reduce treeing	~3 yrs*
		available	- improvement only for thin wall, ie 5 kv cable [2]	~2 yrs* for 5 kv
conductor	- strand filling	experimental	- stop water in strands	~3 yrs*
shields	- bonded to insulation - super smooth - purer carbon blacks	available	- reduces vented trees but requires operating changes	~2 yrs*
		available	- reduce vented trees	~1 yr*
		available	- effect just being studied	~5 yrs
processing	- dry cure - "true" triple extrusion - salt cure - silane	available	- perhaps better control of processing parameters	~1 yr*
		some perhaps in Europe	- perhaps improved interface	~2 yrs*
			- faster cure for larger cable	?
jackets	- polyethylene (including the jacket benefit) - encapsulating PE (including the jacket and PE benefit)	available	- more resistant to damage and moisture than PVC; harder, some neutral indent problems	~3 yrs*
		available	- reduce longitudinal moisture flow, above other designs; some neutral indent problems	~4 yrs*
moisture barriers	- aluminum or lead sheath - swellable powder, tapes - PE coated foils - bonded to jacket - bonded to insulation - other types under development	available in Europe	- stops moisture ingress	~10 yrs*
			- reduces moisture migration	~5 yrs
		soon in North America soon in North America experimental	- all reduce moisture ingress	~5 yrs*

* These values for added life are CONSERVATIVE estimates based on the ranking of all cable changes and options as described in Appendix D.

The estimates of expected life given in Table V are based on water treeing being the main cause of failure for the cables. For such high values of life, other factors will come to play in the ultimate life of the cable, eg thermal aging and direct electrical treeing. Also, the assumption that the effects of the changes are additive comes into question for such long lives. Therefore, the numbers in the Table V, above 30 years, have been reduced by 15%.

Because there is no accurate method for determining the life of cable, the numbers in Tables III, IV and V can only be considered as **TENTATIVE GUIDES** for directing cable purchases. The actual gains for a particular optional cable may be substantially higher than given here. Therefore, other considerations, such as special security requirements for a particular circuit or the need for increasing system reliability, may be the deciding factor in choosing an optional cable design.

Table V

**EXAMPLES OF THE CHANGES AND OPTIONS
AND THEIR EFFECT ON RELIABILITY**

Change	Added Life	Standard Cable	Example Cables				
Full metal barrier	10 yrs	.	.	.	.	.	.
Coated foils	5 yrs	.	.	.	5	5	5
Swellable powders	5 yrs	.	.	.	.	.	5
Encapsulating jacket	4 yrs	.	.	4	.	4	.
Purer semi-con material	4 yrs	.	4	4	4	4	4
"True" triple extrusion	4 yrs	.	.	.	.	4	4
Extruded shields	3 yrs	3	3	3	3	3	3
Strand filling	3 yrs	.	.	3	3	3	3
Tree-retardant material	3 yrs	.	3	3	3	3	3
PE jacket	3 yrs	.	3	.	3	.	3
PVC jacket	2 yrs	2	.	.	.	.	.
Extra clean XLPE	2 yrs	2	2	2	2	2	2
Dual tandem extrusion	2 yrs	2	2	2	2	2	2
Bonded shield	2 yrs	.	.	.	2	2	2
Thicker insulation	2 yrs	.	.	.	.	.	.
"Super smooth" shield	1 yr	.	.	.	.	.	.
Dry cure	1 yr	.	.	.	.	.	.
Salt cure	?	.	.	.	.	.	.
Silane cross-linking	?	.	.	.	.	.	.
Base cable	13 yrs	13	13	13	13	13	13
Expected Life		~ 22 yrs	~ 26 yrs*	~ 29 yrs*	~ 34 yrs*	~ 37 yrs*	~ 40 yrs*

* The sum of the added life exceeded 30 years for these cables; the expected life given has been reduced by 15% as discussed in the text.

NOTE: The numbers in this table are **CONSERVATIVE** estimates based on the ranking of **all** cable changes as described in Appendix D. Buying decisions should not be based wholly on them and other factors should be considered.

5.0 CABLE SPECIFICATIONS AND TESTS

Any specification is basically an agreement between a purchaser and a manufacturer. The purchaser sets out the requirements and the manufacturer agrees to supply a product that meets those demands. The optimum type of specification would describe the product generally and lay out very specific performance requirements including some "simple" tests which accurately demonstrate that performance. Unfortunately, specifying the performance of underground power cables in a meaningful manner to both the user and manufacturer has been difficult. As a result, current specifications contain many details of design and processing so that users will be confident that the product will perform as required. Until appropriate accelerated aging

tests are designed and verified, utilities will continue to be involved in examining the details of manufacture.

Most specifications consist of three parts: a product description, a list of requirements, and a series of tests that demonstrate the product meets the requirements. The requirements include dimensional, physical and chemical qualifications. The tests can be divided into qualification or type tests, production or routine tests, and field tests. Type tests show utilities that the product can be made to high enough standards to be able to perform as required. They also enable manufacturers to evaluate new materials for their product. Routine tests are to show that the required quality is maintained throughout the production run. Field tests are designed to show that the installation was done correctly without causing damage to the cable.

There are three main sets of specifications used as guides by many utilities in Ontario: CSA C68.2, the UECC group specification and AEIC CS-5. These specifications depend strongly on the cable manufacturers' specification ICEA S-66-524/NEMA WC-7. The tests and requirements in those documents and the IEC specification are compared in Appendix C. These documents were written by several different bodies with definite points of view. The CSA specification is a consensus document between Canadian manufacturers and utilities. It is considered as a minimum specification for power cable and utilities may wish to add conditions to it for cable that requires extra features or reliability. The IEC specification is written similarly to the CSA document except that the working group is drawn from many countries. The ICEA specification is written by the manufacturers of cable. It is the foundation document for most of the other specifications. The AEIC and UECC specifications are written by utility groups for their own use and are addenda to the ICEA and CSA specifications.

In this section, the test requirements in the specifications will be compared with respect to the current knowledge about failure mechanisms and with respect to alternate cable designs.

5.1 Qualification Tests

Because cables were not reaching the 30 year expected life, qualification testing has received a great deal of scrutiny in recent years. Much of this effort was directed towards encouraging manufacturers to produce a cable of a superior quality that would give the required in-service reliability.

Most of the qualification tests on polymeric cable were adapted from experience with oil-paper insulated cables. They include straightforward electrical tests such as ac and impulse breakdown, partial discharge and dissipation factor tests with thermally aged cables. This works well with oil-paper insulation since the failure mode is electrical treeing and the aging mechanism is oil and paper degradation from heat. The qualification tests accurately approximate field conditions, and measurements of dissipation factor and partial discharges show the effect of the oil and paper aging quite well; discharges from the initiation of electrical trees add to the losses of the cable and thereby change the measured dissipation.

This history can be seen clearly in the specifications reviewed in Appendix C (Table C-II). However, because of the importance of moisture in the failure mechanism two other tests have been added specifically for polymeric insulations: accelerated water absorption, and accelerated water treeing tests. In addition, the requirements for the standard tests have been made far more stringent.

The accelerated water absorption test looks at the changes in the insulation's dielectric constant and the cable capacitance with the absorption of water. This test does not address the effect of moisture degradation since there is no evidence that the uniform absorption of moisture in the

absence of an electric field degrades the cable's performance. Its value for ensuring the quality of the insulation is probably limited and should be dropped from XLPE specifications.

The AEIC utility group has been trying to develop a method for testing the effect of moisture directly on full size cables. Although an excellent idea in principle, in practice it has been hard to get clear correlations between the results of the test and actual service experience. Both EPRI and the CEA are currently sponsoring research to improve the test method and supply the correlation to service life. Of course as the test becomes more realistic (eg the use of time to breakdown, aging over several years, a large number of samples, controls on the amount and salt content of the water) and much more expensive, the results become more believable. However, it still is an important requirement for new cable insulations.

The other approach to getting an improved product is to make the electrical requirements more stringent. Both the UECC and the AEIC groups have taken this approach. The ac breakdown strength required is substantially higher than required under the IEC specification. Although AEIC insists on 24.4 kV/mm (620 V/mil) breakdown strength, this is probably equivalent to the UECC requirement of 17.3 kV/mm (440 V/mil) since the time between steps in the UECC test is so much longer (0.5 hr. vs 5 min) and the sample so much smaller (3 m vs 9 m). The UECC group also requires a hot impulse test (130°C) with breakdown above 200% BIL on its 3 m sample. The AEIC has requested the cable manufacturers to supply the actual breakdown value "for engineering information". This implies that the AEIC is looking for a new passing level above 125% BIL for a 9 m sample.

The AEIC and UECC specifications differ in the voltage class of the sample cable required for qualification. AEIC requires only that a 15 kV cable be tested to qualify all 5-35 kV cables. However, UECC requires that the sample cable only qualifies cables of the same or lower voltage class. Because of the stringent requirements, it could be very difficult and expensive to carry out the tests on the higher voltage cables. Since initial or thermally-aged electrical strength was not previously a good predictor of cable performance in a wet environment, it is not clear that meeting the hot impulse requirement at 46 kV will guarantee a better performing 46 kV cable than using say a 28 kV cable to qualify all voltage classes.

5.1.1 Modifications to Qualification Tests Because of New Designs

The changes in materials and designs can be divided into two categories: those that improve the water tree resistance of the cable (eg tree retardant compounds, improved shields etc), and those that reduce the rate of moisture ingress (eg encapsulating jackets, strand filling etc). At the moment, the best test available for the first category is some variation of the accelerated water treeing test. Because of the time scale of that test, it cannot evaluate changes that reduce water penetration. It is this second category that will require the most changes in requirements and test procedures.

Some of the kinds of modifications to type testing that will be required because of the new cable designs are given in Table VI. Close cooperation will be required between utilities and manufacturers to arrive at appropriate specifications. Just as important will be the changes to work practices that will be required. For completeness, they are also included in Table VI.

5.1.2 Requalification Requirements

The qualification procedure as outlined in several of the specifications involves a complicated, expensive set of tests. If the requirements for requalification after manufacturing change are made too stringent, manufacturers have a strong disincentive against making minor improvements to processing and materials. Of course this has to be weighed against allowing

changes that are deleterious to cable performance. This question should be examined carefully when the specification is written.

5.1.3 Sample Selection for Qualification Tests

If the manufacturer is required to requalify at various intervals, then it may be appropriate for one utility to supply the cable for a test like the accelerated water treeing test from stock which was delivered by the manufacturer. Although this would become expensive and cumbersome if all utilities supplied cable, one utility carefully storing and supplying the cable would help verify that standard production runs are of the appropriate caliber.

Table VI

EFFECT OF OPTIONAL CABLE DESIGNS ON TYPE TESTING AND INSTALLATION

Optional Design	Type Tests Required
Tree-retardant insulation	- superior performance on accelerated water treeing test
Strand filling	- compatibility of strand filling material and the conductor shield - ability of conductor to block the water - connectability of conductor - especially large sizes of aluminum - perhaps the definition of new work practices
Bonded insulation shield	- strippability requirement no longer needed - need to define adhesion (similar to conductor shield) - need to define new work practices for splicing and terminating
"Super smooth" shield materials	- if effective, should allow for redefinition of protrusion specification to smaller values
Purer carbon blacks	- a definition of purity - perhaps a further specification for dispersion of the carbon black
Processing changes	- this is a major change requiring requalification of the product - bottom line test is performance under accelerated water aging
Alternate jacket material	- some current specs are only for PVC - PE - various kinds each with different properties - should have more stringent mechanical requirements - it may be difficult to specify moisture resistance advantage
Encapsulating jacket	- similar to other jackets - neutral indent into semi-con should be watched - methods should be devised to seal ends to take full advantage of this type of jacket
moisture barriers	- tests to demonstrate moisture stopping capability (currently under discussion in North America and Europe) - methods for handling the barrier at splice and terminations must be developed

5.2 Production Testing

In the specifications, there are many requirements that the manufacturer warrants are met by the product. Production tests are the way the manufacturer shows that the product does indeed meet the requirements of the specification. Experience has suggested that production consistency and quality control are essential for gaining the full expected life of the cable. This puts special emphasis on production testing.

As can be seen from Tables C-III to C-VIII, there are many different tests required during the cable's production. The tests can be divided into several categories:

electrical tests on the entire production run	Table C-III
tests for dimensions	Table C-IV
sample tests for insulation properties	Table C-V
sample tests for shield properties	Table C-VI
physical properties of completed cable	Table C-VII
tests on the jacket	Table C-VIII

The electrical tests on the entire cable are the only methods used which examine the integrity of the entire cable run. The IEC, ICEA and CSA specifications, which are essentially minimum specifications, typically have less stringent requirements than the user-defined UECC and AEIC specifications. This reflects the fact that some users have felt that past cables did not last long enough in spite of passing the required production tests. In general with XLPE insulation, testing for high initial electrical strength has not guaranteed satisfactory long-term performance in moist environments although it can be useful in eliminating gross cable defects. The increased stringency of these tests has not been applied for very long. It remains to be seen if the changes in requirements will lead to improved performance.

The tests on the physical properties of the insulation examine the mechanical strength, the degree of cross-linking and the inclusion content of the insulation after extrusion. The UECC, ICEA and CSA specifications require a tensile strength test and an elongation test with roughly the same values required. Since the AEIC conditions are an addendum to the ICEA specification, AEIC also requires the ICEA tests listed in Appendix C.

The solvent extraction and hot creep tests are primarily checks on how much of the polymer has been cross-linked. Polyethylene changes during the cross-linking process from a thermoplastic material, which deforms when heated, to a thermoset material which resists deformation. This is the reason why XLPE has a higher thermal rating than high molecular weight PE. Because of the expense and time involved, there is a move away from solvent extraction (the uncross-linked material is soluble in organic solvents and the cross-linked part is not) to tests based on the temperature performance of the material (the hot creep test). The less rigorous deformation test is probably sufficient for guaranteeing that the cable has been properly cross-linked sufficiently to meet the thermal operating requirements.

An important part of the examination of the insulation is the inspection for voids (bubbles in the material), contaminants (inhomogeneous material such as charred polyethylene), ambers (translucent particles of discolored polyethylene), and protrusions (projections of semiconductive particles at the shield-insulation interface). CSA, UECC and AEIC are considerably more stringent than the ICEA standard, although AEIC has recently removed the limit on voids between 2 and 3 mils. Most specifications require fairly infrequent insulation inspection since it is costly and time consuming. It is difficult to say whether testing at the levels indicated will guarantee the insulation is free from significant inclusions.

Besides the obvious conductivity requirements for the shields, other significant requirements are concerned with voids in the shields, neutral indentation of the insulation shield, insulation shield strippability (including material left), tear strength of the insulation shield, and low temperature performance. AEIC sets limits for the size of voids allowed in the shields to check for porosity. Although the semiconductive material should equalize the electric stress around any void, there still might be a sufficient discontinuity to initiate a water tree. There could be a problem with the neutral wires or metal tapes penetrating into the insulation shield. This is most evident if encapsulating jackets are used. AEIC and CSA have set limits on the depth of penetration.

Current practices at most utilities in North America require linemen to remove the insulation shield when splicing or terminating the cable. Two tests are used to guarantee that the shield is sufficiently bonded to the insulation and that linemen are capable of removing the shield. Upper and lower limits on the force required to remove the shield are checked with a stripping test. AEIC has a tear test and requirement, ie a specific performance test. When the insulation shield is removed, small bits of semiconductive material are left behind on the insulation. This effect is probably due to the semiconductive material supplied to the cable manufacturers. These particles might lead to problems with splices and terminations. AEIC requires no material to be left that cannot be easily removed. A vague requirement such as this is difficult to use both for the utility and the manufacturer. CSA set an upper limit on the size of the leaving; however, it would still require a lineman to use a grit cloth on the insulation to remove it. Utilities should discuss with the manufacturers what the appropriate limitations are with the current technology.

The UECC group is collecting data on the low temperature strippability of the current insulation shield. If a difference in performance at the lower temperature is found, this information could lead to a requirement suitable for Canadian climates.

Two requirements are tested on samples of completed cables: power factor test, and a shrinkback requirement. The power factor test could be to see if the insulation absorbed too much moisture; however, only the limits used by AEIC are low enough to be a real requirement. (PE is normally <0.05%.) The limit on insulation shrinkback from the conductor is to prevent the creation of a critical void inside a splice that could lead to a failure. After an extensive series of round robin tests, the AEIC and ICEA have agreed on a 50°C, 2 hour, 3-cycle procedure for this test. However, two items might be questioned: the test temperature and the different requirements for alternate cable constructions. The time for the test has been shortened considerably and the temperature lowered from 90°C. While agreeing that a shortened test is probably as effective as the longer one, it is felt that the temperature chosen may be too low. Although 50°C was found to be as effective as the higher temperature for the cables tested, it might not apply to all cables manufactured and the cables are used up to the higher temperature. The other problem is that AEIC allows considerably more shrinkback for strand fill cable and cable with a tape over the conductor. The tape prevents the extruded conductor shield from falling into the strands of large conductors. Since splicing practices are not different for these cables, manufacturers should be encouraged to find a solution to this problem.

There is also a series of tests intended to examine the quality of the cable jacket. These tests concentrate on the mechanical properties of the jacket. If alternate jacket materials are chosen for their better mechanical properties, this should be reflected in changes in the toughness and abrasion requirements. Also, there is no specific test for the ability of the jacket to prevent long-term moisture ingress.

5.2.1 Modifications to Production Tests Because of New Designs

Table VII contains a list of the production tests that should be included in the specification when new designs are going to be used by the utility. Of course these tests are similar to the type tests given in Table VI, but not all tests need to be repeated with every run.

Table VII
EFFECT OF OPTIONAL CABLE DESIGNS ON PRODUCTION TESTING

Optional Design	Proposed Production Tests
Tree-retardant insulation	- a guarantee of uniformity of the polymer from the material supplier
Strand filling	- test ability of conductor to block the water
Bonded insulation shield	- adhesion tests with appropriate values
Super smooth shield materials	- examination of insulation and shields for protrusions at the shield with the tighter restrictions applying
Purer carbon blacks	- test for purity and dispersion on each batch of semiconductive polymer (could be done by compound supplier)
Processing changes	- all production tests examine the production process - difficult to assess differences
Alternate jacket material	- production test values should be changed to those appropriate to material used (eg better abrasion performance)
Encapsulating jacket	- similar to other jackets - neutral indent into semi-con should be watched
moisture barriers	- tests to demonstrate the effectiveness of the moisture barrier

5.2.2 Sampling Frequency for Production Tests

In some ways, the frequency of testing is the most controversial aspect of production testing. In essence, only the tests on the entire cable run can give absolute assurance that the entire cable run performs to that requirement. A test for dimensions or contaminants every 15,000 or 7,500 m or even more frequently, does not guarantee that the entire run is perfect. The extrusion line has to be controlled very carefully to have a product meeting the quality found in such testing.

In the tables in Appendix C, there is a wide range of testing frequencies required among the specifications listed. In most cases, it would be advisable to test more often; however, the tests are expensive. In some cases, it would be worthwhile to pay a premium for the extra assurance. For example, AEIC requires the hot creep test and examination for voids etc. more than twice as often as the other specifications. Data on the strippability of the insulation shield should be monitored to see if those tests should be done more often. A similar view should be taken with cable shrinkback.

5.3 Field Testing

High potential proof testing of new cable installations by Ontario Hydro has been very successful at locating installation problems with cables, splices and terminations. Most of our experience has been with dc testing at 80% of equipment BIL which can locate gross defects in cable accessories quite well. Recently ac proof testing in conjunction with partial discharge measurements has been used to qualify cables in Darlington NGS. The partial discharge test is necessary to guarantee that no incipient damage has been done during the ac test; however, the partial discharge test has been the better probe of equipment condition.

ICEA, IEC and AEIC include proof test limits in their specification. Inclusion of test limits in the specification gives the utility the cable manufacturer's permission to perform the test and encourages the utility to use the test to improve their cable system reliability by eliminating accessory and installation-caused failures.

6.0 CONCLUSIONS

Two main areas concerning underground distribution power cable were examined in this report: current and new cable designs, and cable specifications.

1. Information on the in-service performance of 15- to 20-year-old cable designs has been collected over the past 10 years. Since there is not enough information available at present to create a life function for newer cables, cable life estimates are derived by using the life of the old-design cables as a basis and by using a ranking process for the changes in design (as described in Section 2.0 and Appendix D) to estimate their effect.
 - a) A CONSERVATIVE ESTIMATE of current cable life is given as ~22 years.
 - b) There are several options to the current standard cable design which could offer substantial increases in expected cable life. Depending on the design modification, cables were ESTIMATED to have between 26 to 40 years of life.
 - c) Several of the optional cable designs will require changes in work practices.
2. The cable specifications from several bodies are examined. Most people would agree that it would be best to have a performance specification where what the cable does, not what it contains, is detailed. However, it has been very difficult to functionally describe the desired performance to the satisfaction of utilities and manufacturers. Consequently, specifications now include considerable details about the manufacturing processes used.
 - a) Because of some utility dissatisfaction, there have been many modifications to the specifications over the past few years. Five documents, that are commonly used by Ontario utilities, are reviewed in some detail and compared. There are some large differences between the specifications.
 - b) Optional cable designs are not always included in the current specifications. The modifications necessary are outlined.
 - c) One important aspect that can contribute to overall cable system reliability is field testing. It is recommended that field testing guidelines be included in the specification.

The life estimates, in this report, can only be considered as **TENTATIVE GUIDELINES**; all factors should be considered when deciding on the appropriate cable for a particular application.

The only way to improve on these estimates is to keep records on the performance of the cables that are now in service, and especially the newer ones that are being installed. The CEA is trying to keep records on cable system performance and is offering a micro-computer cable-system database program for utilities. If utilities use this program and feed the information into the CEA, the kind of information required to evaluate and update these estimates could be collected.

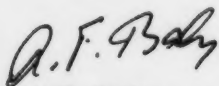
7.0 ACKNOWLEDGMENTS

The author would like to thank the MEA advisors, John Gilmore from North York Hydro, Stewart Reid from Cambridge and North Dumfries HEC, and George Young from Scarborough Hydro. The author would also like to thank Alcan Wire and Cable Products, Canada Wire and Cable Limited, Phillips Cables, and Pirelli Cables for their cooperation in supplying information on current and new cable manufacturing practices.

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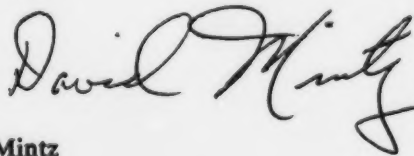


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APPENDIX A

DETAILED COMPARISON OF OLD AND CURRENT CABLE DESIGNS

Table A-I contains some of the changes in manufacturing practices that have occurred in the past 10 to 15 years. Of particular importance are the efforts to produce a cable with clean, void-free insulation, and with semiconductive shields that do not promote insulation degradation. Many of these changes have come out of the realization that moisture can significantly degrade the insulation, and that, in spite of high initial dielectric strength, these materials must be produced carefully and handled properly to obtain maximum cable life.

Table A-I

COMPARISON OF CURRENT AND PAST MANUFACTURING PRACTICES

	Current Manufacturing Practices	Past Manufacturing Practices
insulation	- XLPE - manufactured by UC, BP - extra-clean 4201	- HMWPE or XLPE - manufactured by UC - 4201 <u>not extra-clean</u>
conductor	- copper or aluminum - compact or solid in the smaller sizes, - compressed or standard above 250 kcmils	- more copper than aluminum - more standard strand conductors
shields	- semiconductive material	- semiconductive material
conductor	- extruded PE copolymer material - thermosetting, standard product - bonded to insulation during curing	- extruded thermoset material or carbon black impregnated tape
insulation	- extruded PE copolymer, most likely EVA - thermosetting - UC and in house formulations - not fully bonded to the insulation, - ie stripable	- carbon black impregnated tape or thermoplastic extrusion - some thermoset extrusions - not bonded
processing	- "new" steam or dry cure lines - much better automatic control systems - dual tandem "triple" extrusion	- steam lines with limited automation - if extruded shields, mostly two pass double extrusion with the outer semi-con in separate process
material handling	- clean rooms, enclosed feed systems - attempts to keep dust and dirt out - less attempt at keeping semi-con clean	- open containers - dusty work areas
jackets	- more utilities are requesting them - PVC, PE	- most utilities did not specify them - PVC

When polyethylene was first used for power cable insulation, there were two types in use in North America: high molecular weight (HMWPE) and cross-linked polyethylene (XLPE). HMWPE, a thermoplastic material which deforms during heating, was cheaper, but only offered a continuous operating temperature rating of 75°C. During the cross-linking or vulcanizing

process, heat causes a chemical reaction to bond the polymer chains together. This makes XLPE a thermoset material which resists deformation upon heating, and gives it a thermal rating of 90°C. The service performance of HMWPE in the U.S. has been very poor. In Canada, most utilities opted for the higher temperature rating of XLPE. XLPE has been available from Union Carbide (UC) and others in the 4201 formulation for over twenty years.

During pellet processing, material can be charred and burnt, leaving conductive contaminants. Union Carbide, in the last five years, has improved their manufacturing and inspection techniques to produce an extra clean XLPE for power cable applications. Other compound suppliers are also producing cleaner materials. These materials make it easier for cable manufacturers to meet the contaminant requirements of U.S. and Canadian specifications. It should result in fewer stress enhancements from contaminants in the cable insulation.

Because of costs, some utilities have been using aluminum instead of copper for the main conductor. There is no clear evidence that the conductor material plays a major role on the water treeing degradation process, but it is possible that one metal may be better than the other.

Since the early days of the use of polyethylene as power cable insulation, the biggest changes have been made in the cable shields. Initially, carbon-black impregnated fabric tapes were used over the conductor and insulation to reduce local electrical stresses. Cable, with such shields, tend to grow large water trees which have been associated with cable insulation degradation (see Appendix D). Tape shields were replaced with extruded shields, first on the conductor and then on the insulation. The extruded, carbon-black filled conductor shield was made of a crosslinkable polymer similar to the insulation so that it would be bonded to the insulation. A fully bonded, smooth shield offers fewer initiation sites for water trees to grow.

The insulation shield posed the more difficult problem since it must be removable for splicing and terminating. Manufacturers could not bond the insulation and outer shield together. For a time, they used non-crosslinkable polyethylene for the shields and employed a two-pass extrusion operation to first apply the inner conductor and insulation, and then the outer shield. The shield did not have the same temperature characteristics as the cable and on several occasions it was discovered that the neutral wires penetrated the shield to the insulation in service-aged cables. The two-pass operation allowed contamination of the shield-insulation interface. Eventually, strippable, thermoset materials (many based on an ethylene vinyl acetate (EVA) copolymer) were developed and cable manufacturers could use "triple" extrusion techniques that involve the cable passing through the extrusion process only once. This means that the outer shield-insulation interface was less likely to be contaminated, although this interface may not be as good as a fully bonded one.

The consistent manufacture of large quantities of cable can be difficult and requires good control over the temperatures, pressures and speeds in the process. All manufacturers, whether using steam or dry cure, have high quality control and monitoring equipment on their lines.

Most plants in Ontario use a dual tandem, triple extrusion processing system. A triple extrusion process puts the cable shields and insulation on the cable in one pass of the wire and all parts are crosslinked simultaneously. A dual tandem machine consists of a single extruder head which puts the inner shield on the conductor and a cross-head extruder which simultaneously applies the insulation and the outer shield material. There are usually about 2 metres between the heads. There is a possibility of contamination at this point, but most manufacturers take precautions to reduce the likelihood of that occurrence. A so-called "true" triple extrusion process has a complex cross-head with three feeds so that all three layers are applied in the one head eliminating the possibility of foreign material on the interfaces. However, being inherently more complicated, it is more difficult to set up.

In keeping with the attitude of cleaner insulation, cable manufacturers are handling the materials more carefully than before. The cable insulation is fed by vacuum systems from covered boxes (sometimes in clean rooms) to enclosed extruder feed systems. However, the same precautions are not always taken with the shield materials.

There has been some data suggesting that overall jackets can improve the performance of polymeric power cables [6]. They do offer good mechanical protection for the insulation and may or may not impede the ingress of moisture into the insulation. More utilities are incorporating them into their standard cable.

Table A-II

ESTIMATES OF THE EFFECT THAT MANUFACTURING CHANGES
HAVE HAD ON THE EXPECTED LIFE OF CURRENT DESIGN CABLES

Change	Rationale for the Estimate	Effect on Cable Life
- extra-clean XLPE - improved material handling	- reduces two sources of cable insulation contamination; however, mistakes during extrusion can also contribute - reduces chances of electrical treeing leading to early cable mortality and reduces water treeing	- lower infant mortality - water degradation process slowed could add <u>approx. 2 years</u>* to average cable life
- improved shields	- significant reduction in the production of water trees - some improvement in reducing stress enhancements for electrical trees - still some controversy over the cleanliness of semi-con material; source of moisture and contaminants	- slower degradation due to water treeing depending on the cable's void and contaminant content, * could add <u>approx. 3 years</u> to average cable life
- processing changes	- better control should mean less variability in the cable - should also produce better interfaces - better control of chemical changes eg oxidation	- should result in fewer bad cables with poor records - reduce water treeing at the semi-con insulation border if the changes have not affected the insulation chemically, then could add * <u>approx. 2 years</u> to avg life
- jackets	- less damage to cable during installation - if jackets installed intact, some advantage to reducing moisture ingress (results of recent aging tests) - reduction in neutral corrosion	- mechanical protection would reduce early failures - some reduction in cable wetting mechanical protection and moisture ingress reduction * could add <u>approx. 2 years</u> to avg life

* These values for added life are CONSERVATIVE estimates based on the ranking of all cable changes and options as described in Appendix D.

Table A-II lists the changes that manufacturers have instituted in the last few years and a **CONSERVATIVE ESTIMATE** on the improvement that will result. The estimates are based on a ranking of the relative merit of their effect on cable life. The rankings and the process, used in estimating extended cable life, are given in Appendix D.

In applying the estimates given above, caution must be used when adding the effects of several changes. Premature failure of power cable has been associated with water treeing; however, electrical treeing and thermal aging are also limiting factors on cable life. It is expected that beyond 30 years these factors will begin to play a more significant role and lower the predictions made from Table A-II. Also, the additive nature of the effect of each cable change comes into question as more are included. To reflect these concerns, predictions of cable life above 30 years should be reduced by 15%.

APPENDIX B

OPTIONAL CABLE DESIGNS AND PROCESSES

There have been claims that several optional materials and processing changes can lead to improved product performance. These can be divided into two categories. The first contains changes that have been available for several years, that are proven not to have short term failings and that require, at most, simple well-defined changes in utility practices. The second category contains changes that have not been widely used in service, or that do not have the assurance of short term reliability, or that require major, not well-defined, changes in utility practice. These have been called currently available "experimental" designs.

1.0B CURRENTLY AVAILABLE CABLE OPTIONS

In trying to reduce the effect of moisture on the insulation, Union Carbide and other polyethylene manufacturers have designed crosslinkable polyethylenes which contain additives or have modified structures that reduce water tree growth. Some of the results from short term testing have been very positive for these products; however, the questions of long-term stability of the additive and of whether inhibiting water treeing completely stops degradation need to be answered by in-service experience.

A simple method for extending cable life would seem to be increasing the cable insulation thickness. There is some evidence that this may be significant for cable insulated with HMWPE, but there is not clear evidence in the case of XLPE. This is probably more significant for cables with thin insulation (<15 kV class) than for larger cables.

Moisture degradation, in the form of water trees, can arise from loose shields. These water trees are often very long. This points out the importance of the insulation shield interface. Although the manufacturers have developed very good, strippable materials, the insulation shield interface might be improved by going to a fully bonded material. However, this would entail modifying splicing and terminating practices. Special tools would be required for these operations and staff would have to be trained appropriately to gain any benefits.

Probably the most controversial of all "improvements" is so-called dry-cure (nitrogen) processing. There are two types of processing for crosslinking or vulcanizing power cable currently in use in Canada: steam cure and dry cure. Both are used with chemical crosslinking processes which require high temperatures. In a steam cure line, the temperatures necessary for the chemical process are obtained from high pressure steam. The temperature of the steam is dependent on the pressure. At the end of the pressure tube, the cable is cooled with water. In a nitrogen dry-cure line, the cable is heated by radiant heat in a nitrogen atmosphere. The heat for the chemical process comes from direct radiation from heaters or the vulcanization tube wall. The vulcanization tube is kept under pressure to prevent the formation of large voids in the cable. Temperature and pressure are independent parameters in this process. For the lines in Canada, the cable is cooled by water within the pressure tube but the thermal gradient, and hence the rate of cooling, can be greater than for steam cured lines.

Dry cure processing is presented as a better process for several reasons. One claim is that it reduces the amount of process water in the cable and that this increases cable life. There is certainly less water in the cable at the end of dry curing even with water cooling; however, much of the water that enters the cable occurs during its years in service and is not necessarily put in during processing. Therefore, its effect on increasing cable life is limited. A second claim is that micro voids (on the 1 to 2 μm scale) in the cable are smaller than with cable

processed with steam. Again this is true but there is no evidence that voids on this scale are significant to cable life. Ontario Hydro and AEIC specifications limit voids on the 20 to 50 μm scale. These can be caused by insufficient pressure in the processing. These voids are approaching a size where partial discharging might occur and are more clearly a danger to the insulation. Water trees will grow from voids, and correlations between void and tree size has been seen. However, observable water trees are found only from voids over 10 μm .

There have been some questions raised about the high temperatures that could be used in the dry cure process. There has been a suggestion that the cable may not cure evenly from radiant heat because the cable is not always centered in the tube. This may lead to excessive oxidation of the insulation during processing. However, manufacturers using the process suggest that since cable insulation sag, which might occur in such a situation, has not occurred, this effect is not a problem.

Table B-I

CURRENTLY AVAILABLE CABLE OPTIONS

Alternative Choice	Rationale for Estimate	Effect
Insulation - tree-retardant materials - thicker insulation	- short-term tests show much less treeing - a significant factor in HMWPE cable life - for XLPE, only seems important at <15 kV	- slows water treeing <u>~ 3 yrs</u> * - only for <u>5 kV cable</u> <u>~ 2 yrs</u>
Shields - bonded insulation shield	- reduces initiation sites for water trees	- reduces vented trees <u>~ 2 yrs</u> * - requires operating changes
Processing - dry cure - "true" triple extrusion	- reduces initial cable moisture content - initial tests mixed on whether better - better interfaces, less chance of water tree initiation	- maybe better control <u>~ 1 yr</u> * - of process parameters - reduce treeing <u>~ 2 yrs</u> *
Jackets, Barriers - polyethylene (including jacket benefit) - encapsulating (including jacket and PE benefit) - full Al or lead sheath	- better moisture resistance and strength - reduce longitudinal moisture passage - prevent water entry	- better chance of <u>~ 3 yrs</u> * - slowing moisture ingress - slows moisture <u>~ 4 yrs</u> * - ingress - if not damaged, <u>~ 10 yrs</u> * - stops moisture ingress

* These values for added life are CONSERVATIVE estimates based on the ranking of all cable changes and options as described in Appendix D.

All manufacturers have gone to the single pass, triple extrusion process. There are two systems in use: dual tandem, and "true" triple. The dual tandem process, described in Appendix A, uses two heads to apply the three polymeric layers of a cable. A true triple process uses one head with three feeds to accomplish the process all in a single step. The dual tandem system has most of the advantages of a triple extrusion process, if the cable is protected from dust between heads. It also has the advantage of being easier to set up than a triple feed head. However, the "true" triple process does keep all interfaces free from the atmosphere before curing, and there

is less chance of scratching the inner shield when the cable does not go into a second extruder head.

Although most utilities recognize that they are not complete moisture barriers, jackets can help slow moisture ingress. The standard jacket material for power cables has been PVC. However, polyethylene has advantages as an alternative: it has a lower moisture diffusion rate and it is a tougher material. However, there can be greater problems with penetration of the neutral wires into the insulation shield (neutral indent). Polyethylene comes in many forms as a jacket material (low density LDPE, high density HDPE, and linear low density LLDPE), each with its own set of advantages and disadvantages.

Part of the problem with jackets as moisture barriers is that there is a large space under the jacket because of the neutral wires. An encapsulating jacket has the neutral wires embedded in the jacket so that the space is filled and cannot collect water easily.

Of course, for full moisture protection, the cable can be enclosed in a full aluminum or lead sheath. However, the cost is high, and the skills required to handle such cable are not always available.

Table B-I lists the options currently available, and gives CONSERVATIVE life extension estimates. The estimates are derived in the same manner as described in Appendices A and D. The same cautions, as described at the end of Appendix A, apply to the values in this table.

2.0B MORE EXPERIMENTAL DESIGNS

The designs that are more experimental are listed in Table B-II. Although some are available from manufacturers now, there are enough questions about their performance, often because they have not been on the market long enough, that they should be treated on a trial basis.

Accelerating aging tests on cables have shown that putting water in the conductor strands can speed up the degradation process. Since in-service cables are often found to have water in their conductors, manufacturers are looking for ways to slow the passage of water in the strands. Several methods of strand filling have been proposed, and proprietary materials have been and are being developed. Questions about the filling material's compatibility with the semiconductive conductor shield have been raised. Also, there has not been a decision on the proper test methods for determining moisture penetration although discussions are near completion. Another area that might be a concern is splicing. Although there have been claims that there is no problem, there is still some concern about having a semiconductive material between strands in a splice with large aluminum conductors. Removing the fillers from the conductor before performing the connection would guarantee no problem, but it would be a time-consuming, laborious process.

Also, there are improvements in the area of semiconductive shield materials. There are "super smooth" semi-cons which promise to have less protrusions at the shield-insulation interface. There has been some work here in Canada to suggest that the impurities in the carbon black in the semiconductive material may be a contributing factor in water tree growth. Purer, more expensive carbon blacks are available in Europe and have recently become available in North America.

Besides dry nitrogen and steam curing, there are other processing methods used mostly in Europe. The salt cure process uses the advantage of the high heat capacity of molten salt to assist in the manufacture of large cables. Silane technology uses grafted on radicals to achieve

the crosslinking. This results in a "dry-cure" process not requiring the high temperatures of the traditional peroxide cure.

There are several types of moisture barriers. In France, the space under the jacket contains a water-swellable powder. If moisture gets under the jacket the powder absorbs the water, swells and prevents further moisture penetration. Other designs use swellable powders embedded in a tape to achieve the same result. Semi-impervious barriers, similar to those used on communication cable, are under development for power cable applications. They consist of an aluminum, lead or copper foil coated on both sides with a polyethylene film. The foil is applied longitudinally, folded over and the polyethylene forms a bond in the overlap region. There are two common forms for these shields. The foil can be bonded to a jacket or it can be bonded to the insulation shield. There is a large cost premium associated with this cable and there would have to be significant changes in utility installation practices.

Table B-II

CABLE DESIGNS THAT ARE MORE EXPERIMENTAL

Alternative Choice	Rationale for Estimate	Effect
Conductor - strand filling	- moisture at the conductor leads to accelerated cable deterioration	- stops water from <u>~ 3 yrs</u> [*] traveling along conductor
Shields - super smooth - purer carbon blacks	- improves shield smoothness - <u>may</u> be very important in water tree growth and initiation	- reduce tree sites <u>~ 1 yr</u> [*] - under study <u>~ 4 yrs</u> [*] study
Process Method - salt cure - silane	- can be effectively used for larger cables - alternative dry cure process (Europe)	- unknown ? - unknown ?
Moisture Barriers - swellable powders and tapes - PE coated foils - bonded to jacket - bonded to insulation - other types under development	- under a jacket, can be very effective at blocking longitudinal migration of water - all forms are capable of greatly reducing the amount of water in the cable	- reduces moisture migration <u>~ 5 yrs</u> [*] - reduces moisture ingress <u>~ 5 yrs</u> [*]

* These values for added life are CONSERVATIVE estimates based on the ranking of all cable changes and options as described in Appendix D.

Table B-II gives CONSERVATIVE life extension estimates derived in the same manner as described in Appendices A and D. The same cautions, as described at the end of Appendix A, apply to this table.

APPENDIX C

COMPARISON OF ICEA/NEMA, CSA, UECC, AEIC AND IEC SPECIFICATIONS

This appendix contains a brief outline of several specifications. The information given here is not sufficiently complete for use in specifying cable. The individual specifications should be consulted before tests or requirements are specified.

There are three kinds of testing discussed in most standards: qualification or type testing, production or routine testing, and testing after field installation.

Table C-I

CABLE SPECIFICATIONS BEING REVIEWED

Group	Affiliation	Specification	
		Title	Number
Insulated Cable Engineers Assoc. (ICEA)	Manufacturers	Cross-Linked-Thermosetting-Polyethylene-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy	ICEA S-66-524 NEMA WC-7
International Electrotechnical Commission (IEC)	International Representation	Extruded Solid Dielectric Insulated Power Cables for Rated Voltages 1 kV Up to 30 kV	IEC 502
Canadian Standards Assoc. (CSA)	Canadian Utilities and Manufacturers	Concentric Neutral Power Cable	CSA C 68.2
Association of Edison Illuminating Companies (AEIC)	Large American Utilities	Thermoplastic and Cross-Linked Polyethylene Insulated Shielded Power Cables Rated 5 Through 35 kV	AEIC CS5
Utilities Engineering Coordination Committee (UECC)	Several Large Southern Ontario Utilities	Single Conductor Cross-Linked Polyethylene Insulated Power Cable 5 kV to 46 kV	UECC-1

Table C-II

MAJOR ELECTRICAL QUALIFICATION OR TYPE TESTS

Test	Required Performance				
	IEC	UECC	AEIC	ICEA	CSA
Cable to use in tests	-one sample for all the tests -assume each type must qualify -10 to 15 m of active cable	-28 kV 1/0 qualify 28 and 15 kV -46 kV 4/0 or 350 kcmils qualifies 30 to 46 kV	-15 kV 1/0 qualifies the core for all sizes to 35 kV	-requires no major qualification tests on full cable	-requires no major qualification tests on full cable except power factor and accel water absorption
AC Breakdown	-3 times line-to-ground V for 4 hr -after bend test and heat cycling	-3 m cable -heat cycled -1 to .5 hr steps -440 V/mil	-3 30' cables -new & heat cycled -5 min steps -620 V/mil		
Hot Impulse	-after pd, cold bend, power factor tests and heat cycling -95°C, -100% BIL	-3 m cable -heat cycled -130°C; 200% BIL -10% steps -10 +/- per step	-2 30' cables -new & heat cycled -130°C; 125% BIL -25% steps -3 +/- per step		
Ambient Impulse			-3 30' cables -new & heat cycled -125% BIL -to be changed		
Partial discharge level	-initially -after bending and heat cycling -<20 pC at 1.5 line-to-ground	-sufficient length -<5 pC at 2 & <50 at 4x V-to-G -before & after cold bend test	-15' active cable -<5 pC at 3 & <50 at 4x V-to-G -before and after heat aging		
Power factor	-test as function of volt. & temp.		-max 0.1% for XLPE 0.5% for TRXLPE		-<1% for XLPE
Accel. Water Absorption		-same as CSA			-14 days
Water treeing test - aging		-as per AEIC -for eng. info	-120 days -water in, out -unjacketed		
- ac breakdown			-2 15' cables -260 V/mil		
- ambient impulse			-2 15' cables -for eng. info		
- long term test			-2 15' cables -6 mons, 1 year ac breakdown -for eng. info		
Thermomechanical test			-jacketed cable -14 cycles, 130°C, cable bent -no cracks or hole in jacket		
Requalification period		-every 36 mons -if major change	-if major process change		

Table C-III

PRODUCTION TESTS ON ENTIRE CABLE

Test	Required Performance				
	IEC	UECC	AEIC	ICEA	CSA
Requirement limitation	-need not test all cable if demonstrated good quality control				
Conductor dc resistance	-required	-required		-sample test	-required
Partial discharge test	-<20 pC at 1.5x V-to-G	-<5 pC at 2x V-to-G; <28 pC at 3x V-to-G; <50 pC at 4x V-to-G	-<5 pCs at 2x V-to-G; <28 pC at 3x V-to-G; <50 pC at 4x V-to-G	-extinction minimum 1.3x V-to-G -uses ICEA T-24 <5 pC	-extinction minimum 1.5x V-to-G -uses ICEA T-24 <5 pC
Ac high voltage test	-either ac or dc required -5 min -2.5x V-to-G -112-143 V/mil -once per run require 5 m tested at room temp for 4 hr at 3 V-to-G	-5 min --200 V/mil -modified from ICEA, AEIC	-5 min --200 V/mil -modified from ICEA	-5 min --150 V/mil	-5 min --150 V/mil -modified from ICEA
Insulation resistance		-per ICEA	-per ICEA	-required	-required
Dc high voltage test	-either ac or dc required -5 min ? -6x V-to-G; 270 to 340 V/mil	-15 min -360-400 V/mil -similar to AEIC	-15 min -360-400 V/mil including 133% values	-15 min -360-400 V/mil -133% values lower	-15 min -360-400 V/mil -modified from ICEA

Table C-IV

PRODUCTION TESTS ON SAMPLES FOR DIMENSIONS

Frequency	Required Test				
	IEC	UECC	AEIC	ICEA	CSA
- once per production run	-conductor -insulation thickness -overall diameter -neutral thickness	-shield sizes -lay of tapes and neutral -jacket thickness -diameter of complete cable			
- once per manufacturing reel		-insulation thickness -diam. over insul. shield -diam. over insulation; both ends of reel			-insulation thickness -thickness of shields -jacket thickness
- 10% of reels or coils			-as per ICEA	-all dimensions	

Table C-V

**PRODUCTION TESTS ON SAMPLES
FOR THE PHYSICAL PROPERTIES OF THE INSULATION**

Test	Required Performance				
	IEC	UECC	AEIC	ICEA	CSA
-usual frequency		-every 25K' for <250 kmils; else 50K'	-every 10K'	-every 25K' for <250 kmils; else 50K'	-every 50K'
-tensile strength		-14 MPa minimum -aged 75%		-12.4 MPa min -aged, 75% of unaged value	-12.4 MPa min -aged 75%
-elongation		-250% minimum -aged, 75% of unaged minimum		-250% minimum -aged, 75% of unaged value	-250% minimum -aged, 75% of unaged value
-solvent extraction		-25% maximum		-every 30K' >28 kV else every 100K' -30% maximum	
-hot creep test	-elong 175% max -permanent elongation 15% maximum -every 38K' for 3-core or 66K' for single	-elong 175% max -set 10% max -every 30K' for >500 kmils or 28 kV or more; every 100K' otherwise	-elong 175% max -set 10% max -if failure may use solvent extraction; max 30% -3 per run		-elong 175% max -set 10% max -if failure may use solvent extraction; max 30%
-accel water absorp		-once per run		-required	-required
-voids, contaminants and protrusions		-numbers same as contaminants -voids 2 to 3 ₃ mils <30/in; -contam. 2 to 7 ₇ mils <15/in; -protrusions 10 mils max -every 33K'	-2" sample viewed; to must look at 1 in -voids <3 mils -contam. 2 to 7 ₇ mils <15/in -transluents <50 mils -protrusions 10 mils max; except from conductor into insulation 5 mils maximum	-no test -requirement is insulation free from voids and contaminants visible to the eye	-voids 2 to 3 ₃ mils <30/in; -contam. 2 to 7 ₇ mils <15/in -transluents <50 mils -protrusions 10 mils max except into insulation from conductor shield 5 mils maximum
-heat distortion				-15-25% of unaged value	

Table C-VI

PRODUCTION TESTS ON SAMPLES FOR THE PHYSICAL PROPERTIES OF THE SHIELDS

Test	Required Performance				
	IEC	UECC	AEIC	ICEA	CSA
-voids -conductor -insulation			-every 10K' -<3 mils -<5 mils		
-neutral indent			-every 50K' -15-20 mils max		-15-20 mils max
-tensile strength -unaged					-every 50K' -7 MPa minimum
-elongation @ rupture, aged		-per batch -100% minimum		-per batch -100% minimum	-every 50K' -100% minimum
-volume resistivity -insulation (max)		-every 33K' -50 Ω -m @ 20°C -500 Ω -m @ 110°C -500 Ω -m @ 110°C	-every 50K' -500 Ω -m @ 90°C and @ 110°C	-500 Ω -m @ 90°C	-every 50K' -500 Ω -m @ 90°C
-conductor (max)		-50 Ω -m @ 20°C -1000 Ω -m @ 130°C	-1000 Ω -m @ 90°C and @ 130°C	-1000 Ω -m @ 90°C	-1000 Ω -m @ 90°C
-strippability of insulation shield		-per mfg. reel -6 min, 24 max pounds	-3 per run -6 min, 24 max pounds	-3-4 pounds minimum	-every 50K' -5.9 min, 23.4 max pounds -may use heat
-low temperature -tear test		-for eng. info	-can remove 12" no tearing, no material left behind		
-remaining material -brittleness				-per batch - -10°C maximum	-<20 mils - -25°C maximum
-conductor shield -solvent extract -brittleness		-once per batch -no discontin. - -10°C minimum			
-wafer boil test			-conductor and insulation shield -solvent extraction -no discontin.		

Table C-VII

**PRODUCTION TESTS ON SAMPLES FOR THE PHYSICAL PROPERTIES
OF THE COMPLETED CABLE**

Test	Required Performance				
	IEC	UECC	AEIC	ICEA	CSA
-power factor		-every 100K' --15' sample -<2%		-every 25K' if <250 kmils else 50K' -<2%	-every 50K' -<1%
-structural stability			-every 250K' to 500K' above 50K' -20' sample in pipe; 6 hrs at 90°C, 6 hrs at 130°C -pass pd test -power factor >.1% or .5% if fillers		
-shrinkback		-AEIC test -3 per run	-every 50K' -5 1.5' samples -cycle 2hrs at 50°C; 2hrs at 20-25°C -3 cycles <100 mils		-every 50K' -5 1.5' samples -cycle 2hrs at 50°C; 2hrs at 20-25°C -3 cycles <100 mils

Table C-VIII
PRODUCTION TESTS FOR JACKETS

Test	Recommended Values				
	IEC	UECC	AEIC	ICEA	CSA
-frequency of testing	-every 33K' for 3-core cables; 66K' for single core	-as ICEA -every 25K' for 250 kmils; else 50K'	-every 50K'	-every 25K' for 250 kmils; else 50K'	-every 50K'
-tensile strength -unaged		-as per ICEA -10.5 MPa min.		-thermoplastic PVC - 10.3 MPa Black PE - 9.6 MPa	-thermoplastic (tp) - eg PVC 10.3 MPa min. -thermoset (ts) 12.4 MPa min. and @ 200% elongation 3.4 MPa minimum
-heat aged		-85% of unaged		-PVC 85% of unaged value -Black PE 75%	-(tp) 85% of unaged value -(ts) 50-85% of unaged value
-oil treated		-80% of unaged		-PVC 80% of unaged value	-(tp) 80% of unaged value -(ts) 60% of unaged value
-elongation @ rupture -unaged		-as per ICEA -100% minimum		-PVC 100% min -Black PE 350% minimum	-(tp) 100% -(ts) 300% set 20-30%
-heat aged		-60% of unaged		-PVC 60% -PE 75%	-(tp) 60% of unaged value -(ts) 50-65% of unaged value
-oil treated		-60% of unaged		-PVC 60% of unaged value	-(tp) 60% of unaged value -(ts) 60% of unaged value
-heat distortion		-as per ICEA -50% maximum		-PVC 50% max	-(tp only) --30%
-heat shock		-as per ICEA -one per run -no cracks		-PVC no cracks	-PVC only -no cracks
-low temperature impact					-PVC only -8 of 10 have no cracks at -25 or -40°C
-hot creep test	-for thermoset jackets				-similar tests above
-radial resistivity			-for semi-con jackets -100 Ω -m max		

Table C-IX

LIMITS RECOMMENDED FOR FIELD TESTS

Test	Recommended Values				
	IEC	UECC	AEIC	ICEA	CSA
Dc high potential test	-70% of factory dc test -factory dc test is 6x V-to-G; 270 to 340 V/mil -15 min -new install. only	-no tests were considered	-75% of factory test during installation - 5 min -80% for new complete installation - 15 min -65% after energization - 5 min -factory test -380 V/mil	--5-12 times V-to-G --300 V/mil -15 min	-no tests were considered
Ac high potential test	-2x system voltage for 5 min; at operating voltage 24hr -alternate to dc test	-no tests were considered	-no ac test	-no ac test	-no tests were considered

APPENDIX D

BASIS FOR ESTIMATES OF CABLE LIFE

The expected life of cable is estimated in this report. Because the information necessary to calculate the life function for cable is not available at this time, the approach taken consists of examining the current understanding of the most prevalent failure mechanism, water treeing, determining what effect each cable change would have on the mechanism, ranking the changes by their expected effect, and assigning an increased life expected from the change. The increased life reflects the ranking and is based on an estimate of the added life for the most effective change. To evaluate the increase in cable life, when several changes are applied, the extra life is assumed to be additive.

1.0D CURRENT IDEAS ON FAILURE MECHANISMS

Electrical insulation fails through the process of electrical discharges. These change the character of the insulation and lead to a breakdown path which has sufficiently low electrical resistance to allow large currents to flow at the normal operating voltage. In oil-paper type cable insulations, the typical failures occur because of partial discharges from stress enhancements (eg bubbles in the oil) in the cable leading eventually to a breakdown path. The ability of this type of insulation to withstand discharging depends on the availability of the oil in the cable, the oil being free from moisture, and the thermal degradation of the oil and papers with time. Because the oil can migrate in the cable, there is some self-restoring qualities to this kind of insulating system. However, it does require a lead or aluminum sheath to retain the oil and to keep the moisture out.

The original 30 to 40 year estimates of cable life for solid insulation systems were based on similar thinking. The assumption was that water does not affect the cable's performance and that the primary mechanism for reducing the insulating qualities of the material was thermal in nature. Premature failures of this kind of cable in the late 1960's changed this thinking.

Much of the current thought on failure mechanisms with polymeric insulated power cable centers on the moisture degradation of the insulation. Since initial breakdown strengths of this cable are quite substantial, only by the compromising of the insulation in time can the current breakdown rates have occurred.

It has been proposed that the method of breakdown due to moisture degradation is a four step process:

- moisture ingress
- water tree initiation
- water tree growth
- final breakdown mechanism

To understand how cables fail and the factors that are important, it is necessary to have a clear understanding of each stage and the factors that affect it.

1.1D Moisture Ingress

This stage of degradation deals with the entrance of water into the cable. Water can enter the cable during processing (possible but unusual), during cable storage, during installation, or during its service life. The amount of water necessary to degrade the cable could be relatively

small, ie the inner strands of the cable need not be flooded; however, the concentration of water required for degradation is unknown. Since the cable is often in a moist environment for many years, quite slow moisture ingress could have a significant effect. Obviously, factors which limit invasion of moisture into the insulation will have a substantial effect on this stage.

1.2D Water Tree Initiation

Water trees initiate from small stress enhancements in the insulation or near the insulation-shield interfaces. Since the voltages required to start the growth of water tree structures are much less than those required for electrical trees, small imperfections could be important in water tree initiation.

There are two basic groups of water trees: vented or streamer trees, and nonvented or bow-tie trees. Streamer trees seem to grow from the shield-insulation interface and may initiate from the conductor or insulation shields. Bow-tie water trees originate from contaminants, voids or ambers found in the insulation. Therefore, the initiation of water trees depends strongly on adhesion at the interfaces, the uniformity and cleanliness of the insulation, and the quality of the semiconductive shields.

1.3D Water Tree Growth

After water trees initiate, they grow parallel to the direction of the electric field. Streamer trees tend to grow quite long, often bridging the entire insulation. Bow-tie water trees tend to be more numerous than streamers but are often quite small with their size being proportional to the initiating inclusion. This stage of the degradation process deals with the time required for the trees to grow.

A major difficulty involved with this stage of insulation degradation is determining the point when the water trees have become a threat to the cable. Even a water tree bridging the insulation would not result in an immediate cable failure as would be expected with electrical trees. There is a more general degradation of the insulation system when it is full of water trees. It has been very difficult to correlate water tree size and number with breakdown strength of the material. The feeling is that small water trees are not significant even in large numbers. Streamer water trees, which often grow quite large, are usually considered to be more significant than the smaller but more numerous bow-tie trees.

1.4D Final Breakdown Mechanism

How breakdown occurs in the cable after it has been degraded by moisture is the least understood stage of this failure mechanism. It is assumed that the water trees lead directly or indirectly to electrical trees which ultimately result in a failure. This could occur in several ways. Perhaps some of the electric potential is transferred to the tip of the water tree. If there is some stress enhancement in the region, an electrical tree might be initiated leading to the failure of the cable. Another possibility is that the water tree represents a chemically damaged area of the insulation, perhaps an area where oxidation has occurred. This could lead to the formation of voids large enough to initiate electrical treeing and lead to failure.

1.5D Failures Not Associated with Water Trees

Cables can have failures, without the effects of moisture, in the same way as any other system insulated with a solid dielectric. A discontinuity in the insulation system can lead to discharging, electrical treeing and breakdown. The original estimates of 30-40 year life for cable were based on such mechanisms and degradation of the insulation by thermal aging. This

implies that improvements that affect water treeing phenomena alone (such as stopping water tree growth) may not improve performance as much as expected if cable life is already beyond 35 years. To compensate for this, estimates of expected life should be reduced when they are beyond 30 years.

Utilities should also be aware that they can affect cable life by their handling and installation practices. The life of a cable can be reduced drastically from expected values by rough handling or poor installation.

2.0D FACTORS AFFECTING CABLE LIFE

The factors known to have a bearing on cable failures are enumerated in Table D-I. The difficulty in making accurate estimates of cable life is apparent from the large number of factors and their complexity. The estimates on cable life are made from these factors and the knowledge of the breakdown mechanisms.

It is not just cable design factors that determine expected cable performance. Several different types of factors need to be included and they can be divided into the following areas:

- Cable design
- Cable manufacture
- Installation and handling
- Cable environment - mechanical
- electrical

The effect these factors have on the mechanisms of failure will determine the expected performance of the cable.

2.1D Criteria for Performance

To discuss the operation of cables, it is necessary to define some kind of acceptable and unacceptable performance criteria. The current measure of cable performance is the number of cable failures occurring each year per 100 km of installed plant. Several utilities have determined replacement points for their cable based on this number. From experience, a good cable system in North America has 1 fault per 100 km installed per year or fewer, whereas utilities have tended to start replacing cable when they have 5 to 10 faults. In this report, a very conservative number (3 faults) is used for defining unacceptable performance.

3.0D RANKING AND LIFE ESTIMATES

There are questions about the exact mechanisms involved in all the stages with the final breakdown mechanism being the least understood. The ranking of each cable change or option is based on the significance of the water treeing stage that the change affects and how effective the change is in interfering with that stage of the degradation process.

The clearest and most effective method for improving cable reliability is to prevent moisture from entering the cable. This completely curtails water treeing, although it is very expensive and there are difficulties in obtaining a complete seal. Changes in cable design which reduce moisture ingress are rated the most highly depending on their expected effectiveness at keeping water out. The use of a lead or aluminum sheath, which is the most effective single way of preventing moisture ingress, is considered to be the most effective individual change, and is assigned the highest number of years of extended life. All other cable changes and options are rated relative to this number.

Table D-I

FACTORS SUSPECTED OF AFFECTING CABLE LIFE

Area	Factor	Comments	Effect
Cable Design	Insulation material	- HMWPE, XLPE, tree retardant formulations	- some more resistant to tree growth than others
	Shield design	- fabric tape used alone - stripable - bonded - thermoset, thermoplastic	- affects the number of initiation sites for electrical and vented water trees
	Wall thickness	- independent of operating stress	- thin walled 5-kV cable has poorer performance record
	Operating stress	- volts per mil or kV/mm - use of 133% insulation	- with HMWPE this factor seems to be very significant; less important with XLPE
	Conductor	- material Cu or Al - stranding type, fillers	- may be important for keeping water out of a sensitive area
	Jacketing	- their use - PVC or PE - encapsulating jackets	- should improve resistance to mechanical damage; may slow moisture ingress
	Moisture barriers	- full metal sheath - foils - bonded to insulation shield - bonded to jacket - water swellable powders and tapes	- good water seal but may be damaged mechanically or by corrosion - limits water permeation
Cable Manufacture	Contaminants	- in the raw materials - in insulation - in shields - from carbon black	- considerable improvement in insulation; their importance in the semi-con under study
	Voids	- created during processing - caused during production - controlled by extrusion line pressure	- should not be a problem - current tests would not show problem; full tests expensive
	Interface quality	- between insulation and the shields - compatibility of materials	- important in initiation sites - compromise - strippability vs adhesion
	Processing method	- steam vs dry cure - dual tandem vs true triple	- removal of processing water - both better than 2 pass system - should give smoother interface and fewer initiation sites
	Conductor centering	- too little insulation - too off center to splice	- unusual but serious effect - could lead to accessory faults
	Residual water	- from process, processing water or cooling water	- one possible source of water for water trees
Installation and Handling	Method	- direct buried vs ducts	- help prevent mechanical and chemical damage
	Installation	- control over pulling tensions - mechanical damage	- create voids, break interfaces - break jacket, damage conductor
	Shipping, storage	- sealing cable ends at all times - mechanical damage	- water could collect in strands - as above
Cable Environment	Mechanical	- soil and duct condition - moisture, cycling - available minerals and acids - chemical attack	- lead to water treeing - may increase water tree effect - corrosion of metal, pitting through the shields
	Electrical	- impulses - lightning or switching - level of "normal" stress - testing - ac and dc, maintenance - fault location	- initiate treeing or convert a water tree to electrical tree - some correlation in HMWPE - some concern although not definite

The next most effective way of improving cable performance is the removal of tree initiation sites. Most of the changes which affect this area will also likely affect the final breakdown mechanism. These changes are not as highly rated as the previous ones because the definition of what will initiate a water tree is not complete, and because it is difficult to demonstrate that most initiation sites have been removed because of the large extent of the insulation.

The changes which affect water tree growth were considered to be the least important. Testing so far has been of relatively short duration and it is not clear whether the degradation may still occur in longer, more realistic times.

Because the final breakdown mechanism is not well understood, the changes were not rated with respect to this stage of water tree degradation.

Table D-II
CHANGES AND OPTIONS IN CABLE DESIGN
RANKINGS AND LIFE EXTENSION ESTIMATES

Change	Rank	Estimated Additional Cable Life *
Full metal sheath	1	10 yrs
Coated foils	2	5 yrs
Swellable powders	2	5 yrs
Encapsulating jacket (includes jacket and PE benefits)	3	4 yrs
Purer semi-con materials	3	4 yrs
Single head triple extrusion (includes dual tandem benefit)	3	4 yrs
+Extruded thermoset shields	4	3 yrs
Strand filling	4	3 yrs
Tree retardant insulation	4	3 yrs
PE jacket (includes standard jacket benefit)	4	3 yrs
+Standard PVC jacket	5	2 yrs
+Extra-clean XLPE, improved material handling	5	2 yrs
+Dual tandem triple extrusion, improved process controls	5	2 yrs
Bonded insulation shield	5	2 yrs
Thicker insulation (for 5 kV only)	5	2 yrs
"Super smooth" shield	6	1 yr
Dry curing	6	1 yr
Silane crosslinking	7	?
Salt cure	7	?

+ Available in the current standard cable.

* Conservative estimates of approximate added life; see text for basis.

The base cable design, for which there is field-derived information on its life, has tape semiconductive shields, is unjacketed, and is produced by a two pass process with XLPE insulation which is not extra-clean. All the changes from that cable design, which are outlined in Appendices A and B, have been listed in Table D-II. Each of the changes is given a ranking based on the stage of water treeing that it affects and its expected effectiveness based on the understanding of the degradation process expressed above in this appendix. Although the order in Table D-II does represent the most to least effective change, the differences between several are considered too small to rank separately. COST EFFECTIVENESS IS NOT REPRESENTED IN THIS TABLE.

In estimating the added life, a CONSERVATIVE estimate was chosen for the effectiveness of a full metal moisture barrier. The fact that the average life was being used was also a major consideration. Cable produced before had varying qualities. The difference in life for cable with a serious contamination problem and a clean cable can be over 15 years. However, on the average, it would have much less of an effect because of the variation among the previously produced cables.

The 10 years given in Table D-II represents about two-thirds of the difference between the average life of the old design cable (<15 years) and the predicted average life of cable without the effects of moisture in the cable (30 years). It is reasonable to assume that the coated foils with a method to prevent longitudinal moisture ingress would be as effective as a full sheath. Therefore, the coated foils and swellable powders are rated equally at 5 years; their sum is the same 10 years as is given the full metal sheath. The other factors are rated at less than 5 years in accordance with their ranking. It should be noted that some changes are mutually exclusive (eg the 3 types of jackets: PVC, PE, and encapsulating) and care should be applied in using Table D-II.

To estimate the life of a particular cable, the values for extended life that apply to that cable should be summed and added to the life of the base cable. When the life of the cable exceeds 30 years, two questions are raised: is the additive assumption good, and have other mechanisms come in to play to reduce cable life. Therefore, the estimates of cable life above 30 years should be reduced by 15%. See the main body of the report for some example life estimates.